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HOLOCENE BEACHROCK FORMATION ON THE NICOYA PENINSULA, PACIFIC COAST, COSTA RICA

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Research Advisor: Thomas Gardner

INTRODUCTION

Beachrock is a sedimentary rock, usually a sandstone or conglomerate, containing carbonate cement, and locally derived grains found along the intertidal zone of beaches, most commonly in tropical to subtropical climates (Gischler, 2007). Beachrock commonly occurs between 0° and 40°latitude (Vousdoukas et al., 2007). There is some controversy over the exact range of latitudes of formation, for example Vousdoukas et al. (2007) report latitudes between 20-40° (Vousdoukas et al., 2007), whereas Turner (2005) reports latitudes below 25° as prime for beachrock genesis. Turner states further that beachrock formation is favored by "a well-defined dry season" and where the groundwater ~0.8 meters deep has a temperature of about 21° C eight months out of the year.

Along the beach face beachrock forms, and is commonly found within the intertidal zone (Gischler, 2007), but it may not remain within the intertidal zone, depending on whether the beach is prograding or retrograding (Turner, 2005). Beachrock within the intertidal zone of a beach is exposed to nearly constant mechanical erosion, which is thought to be responsible for the discontinuous nature of beachrock outcrops (Gischler, 2007). Another effect of constant mechanical weathering and erosion is that older fragments of beachrock can be incorporated into newer outcrops, which makes a beachrock an intraformational conglomerate (Gischler, 2007). This can introduce error into any whole rock radiometric ages that attempt to estimate age of beachrock formation, though steps are taken to minimize this possibility.

Geologists have recognized that beachrock ages can be related to changing intertidal levels along a coast, due to changes in eustatic sea level (Turner, 2005). The most common age range globally for beachrock is between 1000-5000 years old (Vousdoukas et al., 2007). It is possible that these ages can be skewed towards an older age because older biogenic material can be incorporated into newly formed beachrock (Vousdoukas et al., 2007). Because beachrock is thought to grow seaward (Vousdoukas et al., 2007), beachrock tends to get younger seaward. Turner (2005) adds that the highly dynamic nature of sandy coasts along which beachrock forms, as well as fluctuating sea levels is responsible for rapid destruction of beachrock. Therefore, beachrock ages tend to be young because unless beachrock is preserved by uplift or eustatic sea level fall, it is destroyed by erosion.

Formation of beachrock is thought to occur in one of two ways: abiotic or biotic. The abiotic methods of formation include: direct cement precipitation, mixing of meteoric and marine waters, and degassing of CO_2 due to tidal flushing (Vousdoukas et al., 2007). Biotic activity is the other proposed method of formation for beachrock. Consumption of CO_2 by autotrophs during photosynthesis or chemolithotrophic bacteria raises the pH of the pore water by deamination of amino acids, dissimilative nitrate reduction, or sulphate reduction (Neumeier, 1999). This alters the chemistry of the microenvironment pores to promote carbonate precipitation (Vousdoukas et al., 2007).

Different mechanisms of formation of beachrock produce different morphologies and chemistries that are helpful in determining environments of formation. Micritic rinds around grains have been proposed as a primary site of carbonate cement nucleation, and are a result of biological activity (Gischler, 2007; Vousdoukas et al., 2007). Often isopachous fringes are found surrounding dark rims, thought to be micritic (Gischler, 2007). Cements exhibit different petrographic attributes based on the dominant water type present; meteoric, or marine. The most common marine cements are: aragonite and high-magnesium calcite, both of which are known to form predominantly in the marine-phreatic realm (Gischler, 2007; Vousdoukas et al., 2007). Aragonite cements often occur as an isopachous acicular fringe surrounding a dark rim, while high-magnesium calcite often occurs as a micritic envelope, and less commonly as high magnesium calcite blades, or scalenohedral crystals (Gischler, 2007; Vousdoukas et al., 2007). Low-magnesium calcite is less common, identified by blocky calcite spar, and is typical of a meteoric environment (Gischler, 2007; Vousdoukas et al., 2007). Not only do cements indicate water composition, but also genesis in the phreatic or vadose zone. Phreatic cements differ from vadose cements because vadose cements may exhibit gravity structures which include pendant and meniscus cements (Gischler, 2007).

The Nicoya Peninsula provides an excellent opportunity for the study of beachrock (e.g., Marshall et al., 2012) because outcrops are common and accessible, exhibit varied composition and facies, and occur across a range of beach environments. Another reason the peninsula is a good study site is due to the mostly homogenous characteristics of the study sites: beaches that are open to the ocean without any physical barriers restricting the flow of marine water, tidal fluctuations that are similar (~2.5 m), and similar climate.

There are three main goals of this research and paper is to:

1. characterize beachrock deposits at outcrop, hand specimen, and microscopic scale.

2. determine how and where beachrock forms using petrographic analyses of the cement, topographic surveys of beach faces, and characterizing beachrock geometries.

3. use radiometric ages of whole shells from beachrock to determine if formations are synchronous, and if their genesis relates to coseismic uplift or eustatic sea level change.

STUDY SITES

The five study sites (Fig.1) on the Nicoya peninsula are located along the western coast of the peninsula. The five sites (from north to south) are: Tamarindo, San Juanillo, Pelada, Garza, and Carrillo.

FIELD METHODS

The methods used in the field in Costa Rica had four parts: topographic hand level surveys coupled with sediment collection, beachrock geometry using a laser rangefinder, beachrock sampling, and shell sampling. Laboratory analyses included: grain size analysis, petrographic analysis, scanning electron microscope (SEM) chemical analysis and imaging, and shell preparation for radiocarbon dating by Beta Analytic. These four methods were used to determine the mechanism and preferred location for beachrock formation.

RESULTS

The topographic surveys characterize the topography of the beach sites, the depth to the groundwater table at a certain time of day, and sample locations for

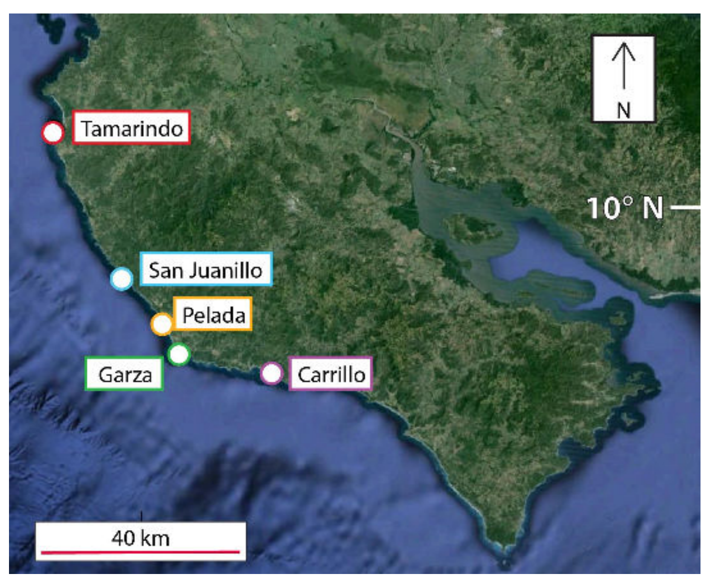

Figure 1. A satellite image of the Nicoya Peninsula and the five study sites.

later grain size analysis. At every surveyed beach, groundwater tables could be identified with auger probes (Fig.2). However, groundwater levels often had to be extrapolated along a portion of a survey transect because the sediment cover of many beaches was too thick near the middle of the survey to intersect the water tables with the auger. The groundwater levels followed the topography of the beaches and were often very close to the surface at the beginning of the survey and then at the end of the survey near the estuary (if there was an estuary). Beachrock geometry surveys showed that each beachrock consistently sloped towards the open ocean, which mirrored results from the topographic surveys. Highest elevation values often occurred on the landward side of the beach while the lowest values occurred on the more seaward side, although some sites had lateral variations to this trend. Beachrock often would be present orthogonal to the steepest slope of the beach, and often appeared near points where through flow from the estuary became return flow on the beach face during low tides. Nine samples were made into thin sections and analyzed under a petrographic scope (Fig.3). Compositions of the beachrock framework grains include: skeletal fragments and lithics, most commonly pyroxenes, but also some plagioclase. Most of the samples had acicular isopachous cements, except for samples CF37, CF41, and CF51 (Fig.3). Some of the thin sections showed brown grungy rinds around the framework grains (CF51, Fig.3), especially CF39. These three were further analyzed using the scanning electron microscope to image the cements under high power, as well as using the Energy Dispersive Spectrometry to get relative element ratios within the cements. The SEM showed that for the most part all the samples examined had very high relative CaO concentrations, and varying MgO concentrations (Table 1). CF41 and CF51 had fairly high relative MgO concentrations, compared to CF37 and CF57 (Table 1).

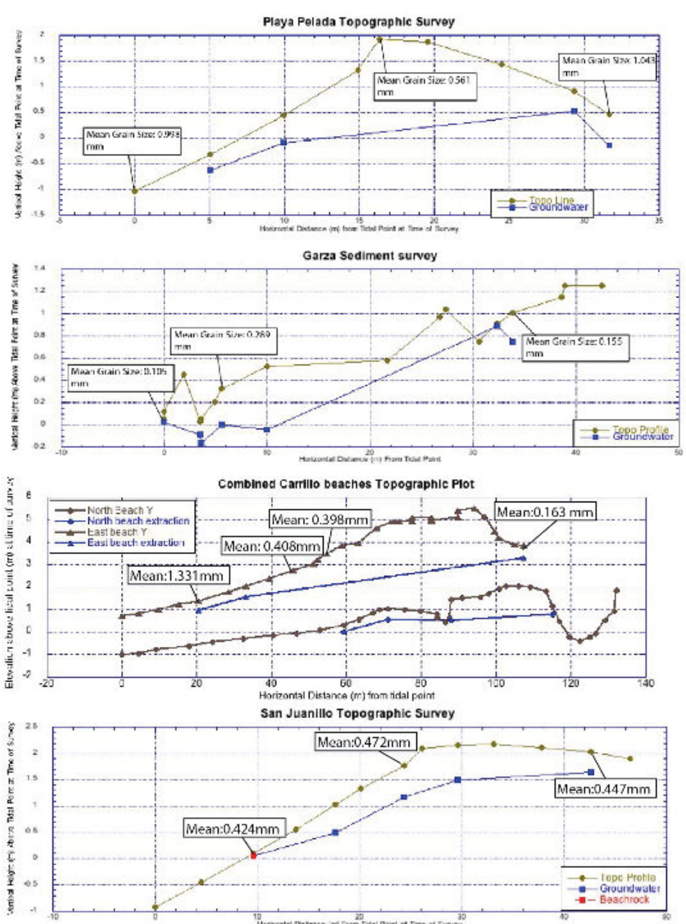

Figure 2. The four topographic/ groundwater surveys conducted at the four study sites, with mean grain sizes shown in the boxes.

Shell samples were collected from beachrock horizons provided that they were thin-walled, cemented within the rock, and mostly complete samples. The shell samples were then prepped by removing as much cement and cemented sand grains from the shells as possible, too eliminate contamination. Radiometric ages from Beta Analytic (Table 2) showed that San Juanillo had by far the youngest beachrock; while Carrillo and Garza had outcrops fairly close in age.

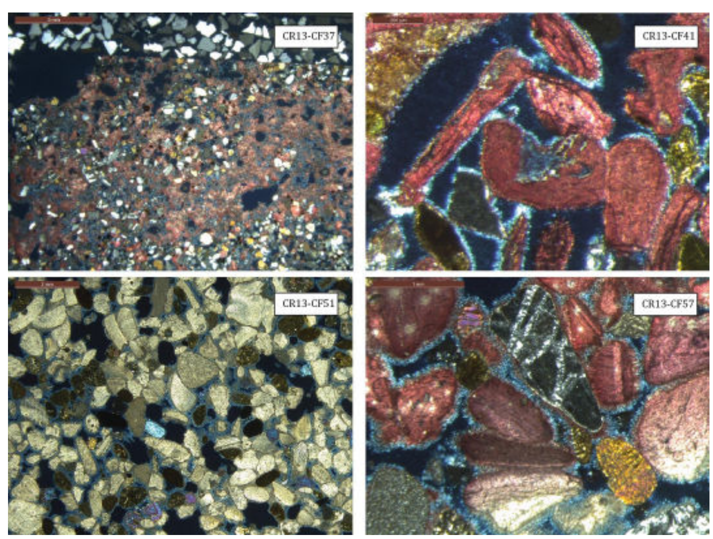

Figure 3. Photomosaic of the four samples that were used in SEM analysis. CF37 scale is 5mm. CF41 scale is 200 micrometers. CF51 scale is 2mm. CF57 scale is 1mm.

Relative Mol % CF37

	Location A				Location B						Location C		Location D (in same "fringe cement" as Loc.C	
Chemical	Spot 1	Spot 2	Spot 3	Spot 4	Spot 1	Spot 2	Spot 3	Spot 4	Bright spot within Loc	2nd bright spot within Loc	Spot 1	Spot 2	Spot 1	Spot 2
O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MgO*	0.77	1.9	3.78	3.06	2.82	2.7	2.43	1.98	1.35	1.29	1.11	1.36	1.42	1.38
Al2O3*	2.09	2.1	1.68	1.71	2.06	2.04	1.69	1.98	1.76	1.71	6.14	5.76	6	5.67
SiO2*	5.56	4.98	5.01	4.52	4.72	4.82	4.6	4.32	5.11	6.83	23.55	22.98	36.03	22.75
CaO	87.9	88.65	81.82	85.73	85.56	83.56	87.69	88.67	45.41	28.01	59.69	64.98	50.84	65.05
FeO*	3.38	2.37	7.54	4.76	4.46	6.61	3.16	2.42	46.1	61.81	8.1	3.77	4.88	3.57
SrO*	0.3	nd	0.18	0.22	0.38	0.27	0.43	0.63	0.27	0.34	1.41	1.15	0.84	1.58
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100

CF41 Relative Mol% Table

	Location A			Location B						Location C				Location D				Location E		
	Spot 1	Spot 2	Spot 3	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot 6	Spot 1	Spot 2	Spot 3	Spot 4	Spot 1	Spot 2	Spot 3	Spot 4	Spot 1	Spot 2	Spot 3
Chemical	mol%			mol%						mol%				mol%				mol%		
MgO	13.53	12.6	15.46	17.27	14.99	16.84	16.78	12.73	17	18.1	13.22	13.99	17.01	18.24	17.99	16.74	19.04	17.74	19.13	19.11
Al2O3	2.09	1.94	1.91	2.55	2.67	2.55	2.83	2.43	2.36	1.98	1.55	2.21	1.7	3.24	3.44	3.36	4.54	2.75	2.77	2.77
SiO2*	12.39	11.75	12	13.52	13.72	13.81	15.04	15.12	13.93	12.01	6.68	8.53	7.39	15.45	16.01	15.43	15.49	11.48	11.74	11.53
CaO	71.69	73.24	69.96	60.24	62.47	58.13	56.92	62.26	57.36	63.76	74.43	72.09	70.01	56.49	56.48	58.21	55.05	61.41	60.43	61.6
FeO	0	0	0	6.06	5.63	8.06	7.74	6.85	8.84	3.41	3.61	2.47	3.27	5.82	5.59	5.73	5.47	6.13	5.4	4.6
SrO*	0.3	0.47	0.66	0.37	0.51	0.61	0.7	0.61	0.51	0.73	0.5	0.72	0.62	0.76	0.5	0.52	0.41	0.49	0.52	0.39
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

CF51 Relative Mol % Table

	Location A			Location B			Location C			Location D			Location E		
	Mol %			Mol %			Mol %			Mol %			Mol %		
	Spot 1	Spot 2	Spot 3	Spot 1	Spot 2	Spot 3	Spot 1	Spot 2	Spot 3	Spot 1	Spot 2	Spot 3	Spot 1	Spot 2	Spot 3
MgO*	10.98	9.16	9.67	7.05	5.41	5.56	4.13	4.57	3.63	4.99	5.12	5.83	4.21	4.2	4.9
Al2O3*	4.17	3.76	4.4	4.21	2.66	3.18	1.45	1.48	1.52	2.07	1.81	1.86	1.85	1.84	2.16
SiO2*	10.78	10.48	11.27	9.61	7.56	7.72	7.48	8.08	6.98	10.17	9.93	11.71	7.03	7.97	8.66
CaO*	68.63	70.52	69.65	74.64	78.73	77.93	82.24	81.48	82.85	77.94	79.21	75.88	82.55	81.01	80.18
FeO*	4.25	5.04	3.72	3.27	4.31	4.27	3.57	2.86	3.7	3.72	2.45	3.4	3.21	3.41	2.87
SrO*	1.19	1.04	1.3	1.21	1.34	1.35	1.12	1.53	1.32	1.11	1.47	1.33	1.16	1.57	1.23
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Relative Mol % CR13-CF57

	Location A		Location B		Location C				Location D
Chemical	Spot 1	Spot 2	Spot 1	Spot 2	ot 1, in volcanic lithic (augit	Spot 3	Spot 4	Spot 5	Spot 1
O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MgO*	2.77	2.37	5.02	4.73	19.56	5.4	5.11	5.01	3.03
Al2O3*	4.04	2.77	4.45	3.74	6.12	4.29	4.55	4.63	3.14
SiO2*	7.96	6.76	15.5	14.33	43.51	14.66	14.47	13.89	9.81
CaO	80.58	83.88	66.49	71.3	20.61	69.86	65.54	71.84	79.76
TiO2*	N/A	N/A	N/A	N/A	0.62	N/A	N/A	N/A	N/A
MnO	N/A	N/A	N/A	N/A	0.38	N/A	N/A	N/A	N/A
FeO*	3.79	3.03	7.36	4.37	9.19	4.68	9.43	3.45	3.06
SrO*	0.86	1.19	1.17	1.53	N/A	1.12	0.9	1.18	1.19
Total	100	100	100	100	100	100	100	100	100

Table 1. Relative mol percents of elements from EDS analysis.

Beach	Old Sample Numbers	New Sample Number	Tested?	Measured Age	13C/12C	Conventional Age	Intercept	Error Range	Reported Values
Pelada	CR13-CF41	No Change	No	N/A	N/A	N/A	N/A	N/A	N/A
Garza	CF14 CF15 CF16 CF17 CF18 CF27 CF43	CFGS1	Yes	2180 +/- 30 BP	+2.2 o/oo	2630 +/- 30 BP	2110	+50/-80	2110 +50/-80 Cal BP
	CF42	CFGS2	Yes	2360 +/- 30 BP	+2.0 o/oo	2800 +/- 30 BP	2310	+30/-30	2310 +30/-30 Cal BP
	CF26	No Change	Yes	2090 +/- 30 BP	+0.8 o/oo	2510 +/- 30 BP	1950	+80/-70	1950 +80/-70 Cal BP
Carrillo	CF36 CF38	CFCS1	Yes	2400 +/- 30 BP	+1.9 o/oo	2840 +/- 30 BP	2330	+90/-30	2330 +90/-30 Cal BP
Juanillo	CF46 CF48	CFJS1	Yes	1060 +/- 30 BP	-0.3 o/oo	1470 +/- 30 BP	860	+50/-90	860 +50/-90 Cal BP
	CF49	No Change	No	N/A	N/A	N/A	N/A	N/A	N/A
	CF50	No Change	No	N/A	N/A	N/A	N/A	N/A	N/A
Tamarindo	CF63 CF64	CFTS1	No	N/A	N/A	N/A	N/A	N/A	N/A
	CF65 CF66 CF67 CF68	CFTS2	No	N/A	N/A	N/A	N/A	N/A	N/A

Table 2. A table showing ages of shell samples.

Carrillo and Garza had beachrock that are generally younger than 2500 years (Table 2).

DISCUSSION

Most of the cements could be classified as aragonite due to their isopachous, acicular nature, which is indicative of aragonite fringes (Vousdoukas et al., 2007). In addition, the relative ratios of elements from the SEM analyses show that most of the samples had very high CaO abundances (Table 1). Two samples (CF41, CF51) had relatively high MgO concentrations (Table 1), which were exhibited in their cement morphologies (Fig.3). These relative concentrations indicate the possibility that CF41 and CF51 have high-magnesium calcite instead of aragonite as the main cement. CF41 is an especially good candidate for further testing on cement composition, since its relative MgO content (Table 1) is within the range that serves as a cutoff for classifying cement as high magnesium calcite. The cement of CF51 had MgO:CaO ratios higher than those for aragonite, based on the criteria given by Vousdoukas et al. (2007) and Gischler (2007), as well as brown rinds surrounding framework grains (Fig.3). The absence of an estuary at the site where the sample was collected would explain the higher MgO concentration, since there is no inflow of meteoric water to dilute the marine water. The petrographic analyses provided valuable insight into where the beachrock formed within the intertidal zone. Almost all the samples contained aragonite cement rinds, except for samples CF37, CF41, and CF51. However, qualitative SEM analysis showed that CF37 had a low MgO concentration. Based on work done by Gischler and Lomando (1997), the light tan microcrystalline cement rinds found in CF37 can be classified as meteoric, which makes sense since the sample was subaerially exposed in the estuary during low tide, and exposed to water from the estuary during high tides. The other Carrillo sample occurred stratigraphically below CF37, had well-developed aragonite rinds and brown rims (similar to those of CF51) surrounding framework grains. The brown rims surrounding the grains might have been micritic, since the crystals were too small to see. According to Vousdoukas et al. (2007) and Gischler (2007) microbial activity can produce micritic rims on a framework grain, providing a substrate on which further cementation occurs, which if true, means the brown rinds have a higher MgO content (Gischler and Lomando, 1997). Micritic rinds would help to explain formation of the beachrock at Carrillo, since they are thought to be the result of microbial activity, which often use framework grains as a substrate to attach to (Gischler, 2007; Vousdoukas et al.,2007).

In this research I have found evidence for two methods of beachrock formation. The first is abiotic mixing of meteoric water with marine water, and the other is microbial activity resulting in a substrate that serves as a nucleation site. Evidence for meteoric and marine mixing is strong, based on the topographic surveys and their shallow groundwater tables, as well as petrographic studies showing cement characteristics (aragonite rinds) that point to formation mechanisms. In addition, the beachrock geometry surveys showed every beach had slope towards the ocean, providing a natural gradient for groundwater to flow along. However, Garza was the only site without an estuary present behind by the study site, possibly due to farmers filling in an old estuary. This begs the question if another method of formation is possible. Because marine water is naturally high in MgO/NaO content, the cement that should form is high magnesium calcite (Folk, 1974). However, the addition of meteoric water, whether from surface flow of throughflow, provides a means of marine water dilution (Folk, 1974). The dilution of MgO ions in solution prevents high magnesium calcite from forming and favors aragonite, or calcite if the concentration of MgO ions is low enough (Folk, 1974). High magnesium calcite will not precipitate unless the Mg:Ca ratio is super concentrated (Taylor and Illing, 1969), which would not occur at any of the study sites except for Garza because every other site had estuaries, which provided meteoric water to the site during low tides. Possible microbial films surrounding framework grains are seen in thin section CF39 from Carrillo and CF51 from Playa Cocál, and it might be possible that these films are present in the rocks at Garza since a high amount of algae grows around the beachrock there, giving credibility to biotic genesis. Garza outcrops had higher topographic elevations from the sand to the water tables, meaning that during low tides they were more isolated from the water table favoring high magnesium cement precipitation, because there is no meteoric water to dilute the high concentration of magnesium ions present in sea water. This is not to say that meteoric/marine mixing is not a possibility because the land behind Garza was estuarine in the past when the beachrock was forming. Since other sites displayed this trend (Pelada, Carrillo, Juanillo) of estuaries existing inland, it would be hard to say that Garza is a special case. Still, one cannot discount the brown rims surrounding framework grains (Fig.3) prior to crystalline cements as coincidence, meaning further testing is needed to determine their origin, though microbial activity does seem plausible.

CONCLUSION

Beachrock along the Nicoya Peninsula is locally derived and most likely formed due from either groundwater mixing with marine water or microbial activity providing a substrate for cement to precipitate. Aragonite cement is dominant at each beach site because meteoric water from the estuaries behind the beaches mixes with marine water, decreasing the Mg concentrations, which favors aragonite formation over high magnesium calcite formation. The role that microbial activity plays is not well understood since evidence of microbial activity was not seen in thin sections from every site. However, it has been shown that microbial activity is linked to micrite precipitation (Gischler, 2007; Vousdoukas et al., 2007), which provides a substrate for further cementation, as seen in sample CF39 and CF51. However, since evidence of this was sparse and evidence of meteoric groundwater is abundant, I must conclude that meteoric throughflow mixing with marine water on the beach face is the dominant mechanism for cement precipitation, and that microbial activity plays a minor role.

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